

Method and device for crushing rock, manipulator to be used in such a device, assembly of a housing and a wire conductor placed therein, and assembly of a housing and a means placed therein.

The present invention in general relates to a method for crushing rock.

5 Such a method can thus be used in clearing concrete structures, but also in under water dredging and such like uses in which rock in general has to be crushed.

10 In all these uses it would be desirable to crush rock in a simple manner into pieces of a small size. For instance the costs of a dredging project may rise high as a result of a small volume percentage of rock, because the device used is unsuitable for dredging this material. Additionally it is not always possible to use explosives. There is a need for a method or device or assembly with which rock
15 can be turned into small pieces in an efficient manner.

According to one aspect of the present invention a method is provided for crushing rock comprising the generation of a shock wave with a preprogrammed form, strength and
20 length of time for crushing rock. Because the shock wave is given such a preprogrammed form, strength and length of time, the crushing of rock produces a desired size of pieces, and/or the crushing of rock takes place over a desired surface of the rock and/or the crushing of rock
25 takes place up to a desired depth in the rock.

In a preferred embodiment of the method according to the invention, such a method is applied repetitively on different locations in or with regard to the rock, in ver-

- 2 -

tical sense and/or in horizontal sense. By repetitively using the method on different locations of the rock an extensive area of rock can be crushed.

- 5 Preferably this comprises the step of bringing an electric wire conductor in the proximity of the rock, and having it exploded by means of supplying a pulse-shaped electric energy.
- 10 As for instance a piece of filamentary electric conductor explodes again and again it is preferred, in order to obtain a continuous process, to have non-exploded parts explode one after the other during bringing the conductor in the proximity of the rock, in other words supplying new
- 15 conductor again and again.

When the rock consists of several layers of rock with separation layers in between them, the shock wave preferably has such a preprogrammed form, strength and

20 length of time that the crushing of rock is enhanced by reflections of the shock wave due to the separation layers.

The invention also relates to a device for crushing rock comprising a filamentary electric conductor, means for bringing the conductor in the proximity of the rock and a device for supplying pulse-shaped electric energy to the conductor, with a quantity to have the conductor exploded for generating a shock wave with a preprogrammed form,

25 strength and length of time for crushing rock.

30

In an advantageous manner the means for bringing the wire conductor in the proximity of the rock are means for repetitively bringing new wire conductor in the proximity

35 of the rock, in which the means for bringing the wire conductor in the proximity of the rock preferably are means for bringing the wire conductor in the proximity of

- 3 -

the rock in almost circumferential shape.

5 The diameter of the circumferential shape is approximately 40 cm, at least a little smaller than the diameter of a suction pipe.

10 The wire conductor is placed in a housing, and preferably has such a shape that the energy released when exploding the wire conductor is aimed at the rock. It is also preferred that the housing of the wire conductor has such a shape that the energy released when exploding the wire conductor is aimed at the rock.

15 In an alternative embodiment the wire conductor is replaced by a means, such as for instance, one or several sparking plugs for generating an electrical discharge, which electrical discharge generates the shock wave with a preprogrammed form, strength and length of time for crushing the rock. When several sparking plugs are used, 20 they are preferably excited in order, resulting in a shock wave being generated. Additionally the means can be formed by at least two electrodes between which a discharge is generated for generating the shock wave.

25 This invention also relates to a manipulator to be used in a device according to the invention for repetitively supplying new wire conductor, and to an assembly of a housing and a wire conductor placed therein, further comprising means for supplying pulsed electric energy to the wire 30 conductor for having the wire conductor exploded and as a result generating a shock wave with a preprogrammed form, strength and length of time, the wire conductor and the housing having such a configuration that the shock wave is aimed, and also to an assembly of a housing and a means 35 placed therein, such as for instance a sparking plug, for generating an electrical discharge, further comprising means for supplying pulsed electric energy to said means

- 4 -

for having the gasses surrounding the means exploded by the discharge, and as a result generating a shock wave with a preprogrammed form, strength and length of time, the means and the housing having such a configuration that the shock wave is aimed.

Further embodiments are described in the attached claims, the contents of which should be deemed inserted here.

Some embodiments of the present invention will be described only by way of example on the basis of the drawing, in which:

Figure 1 shows a schematical view of the soil constitution of a sea bed,

Figure 2 schematically shows the working pattern of a suction mouth of a dredging device,

Figure 3 schematically shows the propagation of a simplified shock wave,

Figure 4 schematically shows the relation between the hydrostatic pressure p and the relative change in volume of concrete and the effects for a shock wave,

Figure 5A shows the relation between the tension and the specific volume in graphic form of pure quartz,

Figure 5B shows the relation between the tension and the specific volume in graphic form of porous sandstone,

Figure 5C shows the relation between the tension and the specific volume in graphic form of pure calcite,

Figure 5D shows the relation between the tension and the specific volume in graphic form of porous calcite rock,

- 5 -

Figure 6 shows the tension-stretch diagram for the one-axis tension situation,

5 Figure 7 shows the tension-stretch diagram for the one-axis deformation situation,

Figure 8 shows a loading cycle,

10 Figure 9 shows the overtaking of the plastic wave front by an elastic relief wave,

Figure 10 shows the dependence of the strength of a rock on the support pressure,

15 Figure 11 shows the yield surface according to the Von Mises criterion (A) and the Mohr-Coulomb criterion (B) in the tension space,

20 Figure 12 shows the set-up of the one-dimensional simulations,

Figure 13 shows the linear elastic sum,

25 Figure 14A, 14B and 14C show the Von Mises strength criterion for $\gamma_0=200$ MPa,

Figure 15A, 15B and 15C show the Mohr-Coulomb strength criterion,

30 Figure 16 shows the failure curve,

Figure 17A and 17B show the energy transfer from water to rock,

35 Figure 18 shows three failure criteria in the p-y diagram,

Figure 19 shows the basic model for the two-dimensional

- 6 -

rotation-symmetrical simulations,

Figure 20 shows the set-up of the two-dimensional rotation-symmetrical simulations,

5

Figure 21A up to and including 21P show the effect of the shock wave on the rock and the gravel,

10

Figure 22 show the areas where the rock fails, the failure pattern,

Figure 23 shows the formation of cracks in a pessimistic interpretation of the results,

15

Figure 24 shows the energy plot of the basic model,

Figure 25A and 25B show the influence of the radius of the load,

20

Figure 26A, 26B and 26C show the influence of the choice of grid,

Figure 27A up to and including 27G show the influence of the thickness of the rock layer, and

25

Figure 28A, 28B and 28C show the influence of the composition of the rock.

30

The present invention will by way of example be described on the basis of a rock layer of 0.1 m, which is imbedded in gravel, which has to be crushed to pieces of a diameter smaller than 0.1 m. To that end the inventive method is used, with which by means of an electric pulse a shock wave is generated. With each shock wave an area of a diameter of 0.5 m has to be crushed. It will however be clear that the present invention can also be used in other fields, such as for instance the clearing of concrete

35

- 7 -

structures.

5 This example is used to give an impression of what kind of shock wave (course of pressure in time, location of the load) is necessary to crush the rock layer in an efficient manner.

10 Before a discussion of the propagation of the wave is at issue, an estimate of the quantity of energy necessary for disintegrating the rock will be given first. For the sake of convenience the manner in which it is disintegrated is left aside.

15 The specific energy, the energy necessary to disintegrate 1 m³ of rock, can be estimated by determining the fracture labour. This is equal to the so-called fracture toughness multiplied by the increase of the fracture surface. The fracture toughness, the energy necessary to create a fracture surface, is the characteristic which can be
20 determined by means of material inspection. The increase in the fracture surface is half the sum of the surface of all pieces and grains that are formed. This surface can be estimated by means of the grain distribution of the crushed material.

25 By means of the theories of elastic waves, an estimate can be made of the efficiency of a one-dimensional elastic wave when it reaches a water-rock boundary surface. One part of the wave will be reflected, the rest will enter
30 the rock layer. The difference in impedance (density multiplied by velocity of sound) between both materials is normative here.

35 Both the strength and the so-called Equation Of State (the pressure as function of the density and the internal energy) of a material are of great influence on the behaviour of a shock wave in a material. The strength of

- 8 -

the material ensures an deviation on the Equation Of State in the tension-stretch diagram. The rigidity of the material and thus the inclination in the tension-stretch diagram in combination with the density is determinative for the velocity of propagation of a shock wave.

Both the failure behaviour and the Equation Of State of rock differ from most solid materials. The yield point of rock increases with increasing pressure. This unlike metals having a constant yield point. The tensile strength of rock being low here. The Equation Of State of dry rock is strongly determined by the crashing of the internal structure above pressures which are of a higher order than the UCS. With increasing pressure the pores of the material will be pressed closed and the grains from which the material is built will rearrange. When the material is fully compressed the rigidity of the material will increase again. The rigidity of the grain material will now be determinative.

When there is water in the pores of the rock these pores cannot be pressed closed entirely: water is not as compressible as air. Whether the internal structure will partly crash is unknown. Possible further examination will have to show what the Equation Of State of (soft) rock saturated with water looks like.

In general rock may fail as a result of:

1. shearing: As soon as a tension situation arises which is situated on the yield surface, the rock will plastically deform. This is accompanied by the growth of micro cracks. If this situation persists long enough with sufficient plastic deformation, the rock will fail. In this way the strength of the material deteriorates down to a residual strength which can be compared to the strength of sand.

2. traction: Rock has a limited strength when the

- 9 -

hydrostatic pressure is low. Below a certain negative pressure the material even has no strength at all. When the tensile strength is reached a traction crack will arise. After that the material can no longer absorb
5 negative tensions. Shearing and pressure tensions can still be absorbed.

3. pressure: When the pressure tension will get high enough, the rock will also fail on the hydrostatic axis. The structure of the rock will crash and the rock will
10 crumble. There is no uniform criterion at hand from the literature applicable to this crumbling. Non-porous rock will not crash until under high pressures. The calcite and/or quartz will first go through (several) crystal phase transitions.

15 It is not easy to determine beforehand, how a shock wave will propagate through a rock. The problem will become quite awkward when the shock wave is situated in a spacial geometry. It is still preferable to obtain some indication
20 beforehand about the propagation, so that when used in practice there is something to go by. Because of the complexity it was chosen to calculate the propagation with the finite elements of the program AUTODYN.

25 One-dimensional simulations will be started with. The outcome of the numeral elastic sum corresponds to the analytical sums which have been made prior to the simulations. In the simulations with the Von Mises and Mohr-Coulomb strength criterion the following strikes:

- 30
- * As the pulse goes further through the rock it deforms.
 - * The front of the wave splits into an elastic and a plastic part. The elastic part has a higher velocity
35 of propagation.
 - * the pulse is topped off, an elastic discharge wave overtakes a part of the plastic wave front.

- 10 -

The behaviour of the rock, concrete and soil is usually shown by a failure curve. From these failure curves it clearly appears that the yield point depends on the prevailing pressure. For this reason the Mohr-Coulomb strength model is chosen to model the strength of rock in AUTODYN.

In words this strength model comes down to that at a certain hydrostatic pressure p the difference between two main tensions cannot become larger than the value of the yield point y belonging to that pressure. When the yield point is reached then a rise of the largest main tension automatically results in the other main tension rising along. The tension situation can then be found back in the failure curve at a higher pressure.

From the limited data available of the Equation Of State of dry rock without pores it follows that at pressures in the range of 0 to 2 GPa the Equation Of State can be approximated by a straight line. For that reason and because of the lack of data of water-saturated rock the linear EOS has been chosen for. The expectation is that the water in the pores will ensure that the components from which the material is built up cooperate as parallel springs. The bulk modulus can then be calculated with the volume percentage and the bulk modulus of each separate component. The rock is now depicted as a homogeneous material with this new bulk modulus.

Of the available failure criteria only the criterion for the maximum tensile strength could be used. A maximum value of 3 MPa (traction) was chosen which may reach one of the three main tensions. Here the material fails when one of the three main tensions reaches the maximum value, or all three at once along the hydrostatic axis. After failure the material can only absorb pressure tension.

- 11 -

There are five areas in which as a result of a simulation of a two-dimensional situation, the so-called basis model can be expected that the rock will fail

1. Zone in which pulverization may be expected.
- 5 2. Radial cracks as seen from the crater.
3. Spalling as a result of reflection against the boundary rock-gravel.
4. Traction cracks as a result of a relaxation traction wave near the axis of symmetry.
- 10 5. Spalling as a result of reflection near the axis of symmetry.

Calibration of these simulations with experiments is necessary to prove how the rock exactly fails and which failure pattern goes with it. With the results of these simulations as only information, a maximum piece size of approximately 10 cm appears to be a safe estimate.

From the simulation of the basic model follows that with an annular load a shock wave with an energy of about 29 kJ enters the rock layer. This shock wave ensures, that spread over a diameter of approximately 0.5 m, different areas are formed within which the rock fails. Here some pieces may be formed with a maximum size of 10 cm. The rest of the material will be more finely spread.

If it is assumed that a quarter of the energy released at explosion of the wire enters the rock layer, about 120 kJ will be necessary with this method, to obtain pieces of maximal 10 cm in a rock layer which is 10 cm thick. With the crushed volume of 0.02 m³ the specific energy of this method can be estimated at 6 MJ/m³.

Besides the simulation with the basic model tests have been carried out in which the influence of the various parameters has been examined. The conclusions that can be drawn from them are:

- 12 -

* An annular exploding wire is an effective manner to apply a quantity of energy over a large area in a spread way. If it is desired that an area with a radius of 25 cm fails, a loading radius of 20 cm appears to be a good choice.

* If the layer of rock is twice as thick a hole with a radius of 20 cm in stead of 25 cm arises. If the same load is put on a half finite rock layer, a hole with a half ellipsoidal shape will arise. This hole has a diameter of about 55 cm and a maximum depth in the centre of the hole of approximately 20-25 cm.

In the description given below of a exemplary embodiment of the present invention symbols will appear regularly. In order to elucidate the understanding of these symbols a list of symbols is shown below.

List of symbols		unit
A	:surface of cross-section on which F_L is active	m^2
A_{fr}	:fracture surface per unit of volume	$1/m$
c	:velocity of propagation of an elastic wave	m/s
c_1, c_2	:velocity of propagation in material 1 and 2	m/s
CCS	:Confined Compressive Strength	N/m^2
d	:grain diameter	m
D	:damage parameter	-
dl	:the distance bridged in a time dt by one pulse	m
dt	:the time that the force F_L is active	s
E	:Elasticity modulus	N/m^2
E_0, E_1	:internal energy of the material before and after the front of the shock wave	m^2/s^2
EOS	:Equation Of State situation equation	-
F_L	:longitudinal force active on a given cross-section	N
G	:gliding modulus	N/m^2
G_{IC}	:fracture toughness	N/m
HEL	:Hugoniot Elastic Limit	N/m^2
K	:bulk modulus	N/m^2

	K_i	:bulk modulus of a component of rock	N/m^2
	K_{IC}	:critical tension intensity factor	$Nm^{3/2}$
	K_s	:bulk modulus of grain material	N/m^2
	K_w	:bulk modulus of water	N/m^2
5	K_0	:bulk modulus of the rock in drained situation or with air in the pores.	N/m^2
	m	:relation pressure and tensile strength of rock	-
	m	:the mass on which F_L is active	kg
	n	:porosity	-
10	p	:hydrostatic pressure	N/m^2
	R	:reflection coefficient	-
	s	:fracture degree of rock	-
	s	:material constant	-
	SE	:Specific Energy	N/m^2
15	t	:time	s
	TS	:Brazilian Tensile Strength	N/m^2
	u	:velocity of material	m/s
	UCS	:Unconfined Compressive Strength	N/m^2
	V_s	:velocity of propagation of a shock wave	m/s
20	W	:energy of a shock wave	N/m
	W_I	:energy of an incoming shock wave	N/m
	W_R, W_T	:energy of the reflection and transmission shock wave	N/m
	W_{fr}	:fracture labour	N/m^2
25	y	:yield point or yield	N/m^2
	y_0	:constant yield point or yield with the Von Mises criterion	N/m^2
	α_i	:volume percentage of a component of rock	-
	Δt	:duration of pulse	s
30	$\epsilon_x, \epsilon_y, \epsilon_z$	:stretch in x, y and z direction	-
	γ	:surface tension	N/m
	μ	:impedance relation of two media	-
	ν	:lateral contraction coefficient	-
	ρ	:diviatoric length in tension space	N/m^2
35	ρ	:density	kg/m ³
	ρ_0	:total density of water saturated rock	kg/m ³
	ρ_1, ρ_2	:density of material 1 and 2	kg/m ³

- 14 -

	ρ_s, ρ_w :density of grain material and water	kg/m ³
	σ :tension	N/m ²
	σ_1 :largest main tension	N/m ²
	σ_{1r}, σ_{1w} :largest main tension in rock and water	N/m ²
5	σ_2, σ_3 :the other main tensions	N/m ²
	σ_{1n}, σ_{3n} :normalized largest, smallest main tension respectively	-
	σ_{HEL} :tension level of the Hugoniot Elastic Limit	N/m ²
	$\sigma_{i,max}$:maximum tension on traction of one of the	
10	three main tensions	N/m ²
	σ_I :tension of incoming wave	N/m ²
	σ_R :tension of the reflected wave	N/m ²
	σ_T :tension of the transit wave	N/m ²
	$\sigma_x, \sigma_y, \sigma_z$:tension in x, y and z direction	N/m ²
15	τ_n :standardized sliding tension	-
	ξ :hydrostatic length in the tension space	N/m ²

In dredging projects it occurs quite often that a part of the material to be excavated consists of rock. A dredging device which is designed for sand, gravel or clay is not always suitable for excavating this material. Also a sludge sucker comes across too a hard piece in a project that mainly consists of soft rock. In that way as a result of a small percentage of volume of (hard) rock, the costs of a project may rise high because of abnormal wear or overload of the device. Additionally it will not always be possible to use explosives in such cases, because of the high costs, the great depth of water or because it is not allowed.

A device or mounting a provision on an existing device, which in an efficient manner can crush small volumes of rock may be a useful addition to the arsenal of devices from which a dredger can choose.

Below such a device, and a new method are described in which by means of an electric pulse a shock wave is

- 15 -

generated. With this shock wave rock can be crushed..

In an offshore mining project sediment containing minerals is won with a dredging device standing on the bed. In a diagram the build-up of the soil is as shown in figure 1.

Essential is that the gravel layers, in which the precious minerals are present, are completely removed (no spilling). Excavation, takes place with a suction mouth which can make movements like a sewing machine (vertical penetration, raising, lateral movement etc.).

Figure 2 schematically shows the method with the pattern that the suction mouth makes as seen from above. It is expected that said suction mouth will have problems penetrating the cemented layer, when one works in the conventional manner.

According to the invention a provision on the suction mouth crushes a rock layer of a thickness of 0.1 m and a pressure strength of 10 Mpa. Here it is ensured that the pieces are of a size smaller than 0.1 m. The suction mouth has a diameter of 0.5 m and can exert a force of 150 kN on the bed in all directions.

It appeared that rock can be crushed when it is hit by a shock wave. Shock waves can among others be generated by explosives. The inventive method for generating shock waves, is sending an electric pulse with a high power during a fraction of a second through a conductive wire, for instance copper or aluminium. This wire will because of its electric resistance rise so high in temperature, that it changes into gas or plasma phase. This gas will expand so fast that a shock wave is realised.

Before the propagation of the shock wave is described, first an estimate is made of the energy which is required

- 16 -

for the disintegration of rock, the so-called fracture labour. It is left aside her in which manner disintegration takes place.

- 5 The specific energy can also be calculated. Here the fracture labour W_{fr} is determined:

$$W_{fr} = G_{IC} \times A_{fr} = 2\gamma \times A_{fr} \quad (N/m^2) \quad [2.2]$$

in which:

- 10 G_{IC} : fracture toughness (J/m^2)
 A_{fr} : surface of fracture per unit volume (m^2/m^3)
 γ : surface tension (J/m^2)

These terms are discussed below.

- 15 Important for determining the fracture labour is the surface tension γ or the "fracture toughness" G_{IC} , both material characteristics. The factor 2 in equation [2.2] is a result of the definition of γ . In case of fracture an additional surface of twice the fracture surface is generated. The fracture toughness can be calculated with:

$$G_{IC} = \frac{1-\nu^2}{E} K_{IC}^2 \quad (J/m^2) \quad [2.3]$$

- Here K_{IC} is the "critical stress intensity factor", material characteristic which has to do with the critical increase in tension around a crack tip. K_{IC} can have the following values:

$K_{IC} = 0.2 - 1 \text{ MPa m}^{1/2}$ for sandstone
 $K_{IC} = 1.5 - 2.7 \text{ MPa m}^{1/2}$ for granite
 $K_{IC} = 0.5 \text{ MPa m}^{1/2}$ for rock with an E modulus of 4 GPa

- 30 The lateral contraction coefficient $\nu = 0.25$ and an E modulus of 4 GPa gives this with equation [2.3]:
 $G_{IC} \approx 59 \text{ J/m}^2$ with $K_{IC} = 0.5 \text{ MPa m}^{1/2}$
 $G_{IC} \approx 9.4 \text{ J/m}^2$ with $K_{IC} = 0.2 \text{ MPa m}^{1/2}$

- 35 For soft rock (10 MPa) which has been chosen as basic

- 17 -

material it can be expected that the fracture toughness is low (10-20 J/m²). The fracture toughness however, depends on the velocity of deformation under which a fracture arises and will as a result of it increase. Additionally the fracture toughness will also increase as a result of water in the pores. A fracture toughness of $G_{IC} = 50 \text{ J/m}^2$ will further be assumed. This estimate has been made on the basis of very few data, completed with a number of assumptions and as a result of this only indicates the order.

The increase of the fraction surface can be calculated by taking the sum of the surface of all pieces and grains which are formed and dividing this sum by two. After all as a result of each fracture two fracture surfaces are created. In the calculation of the surface use can be made of the relation surface:volume of a grain. If a cube-shaped grain is assumed:

$$A_{fr} = \frac{1}{2} \frac{6\sqrt{3}}{d} = \frac{3\sqrt{3}}{d} \quad [2.4]$$

is valid in which:

A_{fr} : the fracture surface per cubic meter of crushed rock. (m²/m³)

d : the grain diameter, the diagonal of the cube. (m)

By means of the grain distribution of the crushed material the total fracture surface can be determined.

Examination of the soil proved that about 65% of the rock consists of calcite particles with a grain diameter between 0.01 and 0.03 mm. Furthermore the rock consists of about 35% of quartz and other particles with a grain diameter of about 1 mm. If it assumed that the rock is completely crushed to grains with [2.4] follows:

$$A_{fr} \approx 2,5 * 10^5 \text{ m}^2/\text{m}^3.$$

- 18 -

With a fracture toughness of G_{IC} of 50 J/m² and an increase of the fracture surface $A_{fr} = 2,5 * 10^5$ m²/m³, the fracture labour for totally crushing the examined rock material to grains according equation [2.2] will be:

5

$$W_{fr} \approx 13 \text{ MJ/m}^3$$

If the rock is not completely crushed to grains but large pieces are created, the fraction surface is many times smaller and less energy is necessary. When for instance rock is divided into cubes of 10 cm W_{fr} will be ≈ 3 kJ/m³. This quantity of energy is negligible with respect to the energy necessary for total crushing.

Independent of the method used for disintegrating rock, the fracture labour can be estimated by multiplying the fracture labour necessary for total crushing by the volume percentage of the rock which is crushed in the process.

The intention of the method with the exploding wire is to create a hole with a diameter of 0.5 m in a rock layer of 0.1 m thick with each generated shock. The volume that has to be crushed each time will then amount to 0.02 m³. The energy necessary added to the layer of rock for total crushing will be approximately 250 kJ.

It is noted in this calculation:

- * Fracture only arises along the grain boundaries, not right through the grains.
- * All grain bindings are broken at crushing.
- * The grains have the shape of a cube.

Of the three parameters that have to be determined (G_{IC} , volume percentage of the crushed part and the grain distribution of the crushed part) the fracture toughness is the hardest to determine. It is different for each kind of rock and moreover depends on the velocity of defor-

- 19 -

mation and the presence of water in the pores.

The G_{IC} can among others be determined with a "Split Hopkinson Bar Test". In this test a test piece is pulled apart hydraulically or by means of a falling weight. By determining the fracture surface which is formed and the necessary energy an estimate of G_{IC} can be made. Moreover with this test the influence of the velocity of deformation and the presence of water on the fracture toughness can be determined.

The velocity of propagation of a simple longitudinal wave with a plane wave front is:

$$c = \sqrt{\frac{E}{\rho}} \quad (m/s) \quad [3.1]$$

Here the elasticity modulus E depends on the velocity of deformation. The instantaneous velocity of material u of a particle is directly related to the instantaneous tension on that point. This relation can be derived from the second Law of Newton:

$$F_L dt = dm u \quad [3.2]$$

in which:

- F_L : the longitudinal force active on a given cross section (N)
- dt : the time that the force is active (s)
- dm : the mass on which the force is active (kg)
- u : the velocity of material of the mass (m/s)

With

$$\sigma = \frac{F_L}{A}$$

and $dm = \rho A dl$;

in which dl is the distance which the pulse has bridged in

- 20 -

the time dt. [3.2] will now be:

$$\sigma = \rho c u \quad [3.3]$$

The bulk modulus of a porous material is influenced by the presence of water in the pores. As the velocity of deformation increases, the water will get less chance of pouring out of the pores. An undrained situation arises, the water is locked up in the rock. The bulk modulus in such a case can be calculated from the moduli of the components:

$$K = \frac{n \left[\frac{1}{K_s} - \frac{1}{K_w} \right] + \frac{1}{K_s} - \frac{1}{K_0}}{\frac{n}{K_0} \left[\frac{1}{K_s} - \frac{1}{K_w} \right] + \frac{1}{K_s} \left[\frac{1}{K_s} - \frac{1}{K_0} \right]} \quad (N/m^2) \quad [3.4]$$

in which:

- K : bulk modulus of the water saturated rock in the undrained situation.
- K_s : bulk modulus of the grain material
- K_w : bulk modulus of the water
- K₀ : bulk modulus of the rock in the drained situation or with air in the pores.
- n : porosity.

Equation [3.4] is called the Gassmann equation and is from the acoustic, sound waves in porous media. Small elastic deformations are assumed here.

When an elastic, longitudinal tension wave approaches a free surface at a right angle, the wave will reflect and change of sign. A pressure wave will become a traction wave after reflection. When this wave does not reach a free surface, but a boundary surface with another elastic material, then a part of the wave will be reflected and the rest will be guided through the other material. Valid here is:

- 21 -

$$\sigma_R = \frac{\rho_2 c_2 - \rho_1 c_1}{\rho_1 c_1 + \rho_2 c_2} \sigma_1 \quad \sigma_T = \frac{2 \rho_2 c_2}{\rho_1 c_1 + \rho_2 c_2} \sigma_1 \quad [3.5]$$

in which:

σ_I : the tension of the incoming wave (N/m²)

σ_R : the tension of the reflected wave (N/m²)

σ_T : the tension of the transit wave (N/m²)

5 ρ_1, ρ_2 : the density of the two materials (kg/m³)

c_1, c_2 : the velocity of propagation of elastic waves in the two materials (m/s)

10 It can be seen that depending on the characteristics of both materials a traction or a pressure wave arises at reflection.

The transfer of energy can be determined with the relation:

15

$$W_I = W_R + W_T \quad [3.6]$$

With W_I , W_R and W_T the energy of the incoming wave, the reflected wave and the transit wave, respectively. The energy of a square-shaped wave with a plane wave front is:

$$W = \frac{1}{2} c \Delta t \frac{\sigma^2}{E} \quad (N/m) \quad [3.7]$$

20 For a triangular pulse, it is further valid:

$$W = \frac{1}{6} c \Delta t \frac{\sigma^2}{E} \quad (N/m) \quad [3.8]$$

in which is:

Δt : the duration of the pulse (s)

σ : the tension peak of the pulse (N/m²)

25

With [3.5], [3.6] and [3.7] or [3.8] combined the energy transfer by an electric pulse from the one medium to the other can now be calculated.

- 22 -

Above an energy value has already been given which has to be supplied to the rock in order to crush it completely. With the theories of elastic waves, an estimate can be made of the efficiency of a one-dimensional elastic wave when it reaches a water-rock boundary surface. Here it regards the theoretical case of a one-dimensional wave with a rectangular tension course. The material characteristics are chosen as follows (relation [3.1] is valid):

	water	rock
ρ (kg/m ³)	1000	2500
c (m/s)	1500	2760
E (GPa)	2.3	19

Table 1: the chosen material characteristics for the calculation according to the elastic wave theories.

As described above, for the energy necessary for total crushing, the order of 13 MJ/m³ followed. For a rock layer of 0.1 m thick $W_T = 1.3$ MJ/m² is valid for the energy of the transit wave right after the boundary surface water-rock. For the incoming wave would then be valid: $W_I = 2.1$ MJ/m² with

$\sigma_I = 1$ GPa and $\Delta t = 6.5 \mu s$ with [3.7] follows: $W_I = 2.1$ MJ/m²

With equation [3.4] and table 1 then follows:

$\sigma_R = 0.64$ GPa and $\sigma_T = 1.64$ GPa

And with [3.7]:

$W_R = 0.8$ MJ/m² and $W_T = 1.3$ MJ/m²

As will be described later, this situation will be simulated with the programm AUTODYN.

It follows that about 40% of the energy is reflected and

- 23 -

remains in the water. So when an elastic pulse passes the boundary surface water-rock at a right angle, only 60% of the energy of said pulse enters the rock material.

5 The equations used here are valid for an elastic material in a one-dimensional situation. Because exactly here plastic deformation and fracture are wanted, this sum only is a part of the estimate of the order of the necessary tension, length of pulse and energy of the shock wave. The
10 tension and the length of the pulse can according to equation [3.7] be adapted without changing the supplied energy.

15 The behaviour of solid substances under an intense pulse load can roughly be divided into three areas on the basis of the intensity of the tension waves which occur:

- 20 1. Elastic waves. In a load below the elasticity limit the material behaves elastic as described in chapter 3. The Law of Hooke is valid.
- 25 2. Elastic-plastic tension waves. In a load above the elastic limit the material behaves plastic. Large deformations occur and often the material fails. The elastic limit or the strength of the material determines for a large part the behaviour of the tension wave. A tension wave in this area consists of an elastic part, with an intensity equal to the elastic limit and a plastic part.
- 30 3. Shock waves. At a tension intensity which is some orders of magnitude higher than the elastic limit, the material behaves hydrodynamic: like a liquid. The strength of the material does not play a part any longer. The wave front of a shock wave can be regarded as a discontinuity. This is the case when
35 the velocity of the propagation of the wave is larger than the velocity of sound, the velocity of propagation of an elastic wave.

- 24 -

After this the theory of shock waves and elastic-plastic tension waves in a rock will be discussed on the basis of the generally known theory. This general theory is mostly concentrated on tension waves in metals, such as occur in ballistic problems (penetration of missiles). Tension waves show a deviating behaviour in a material such as rock or concrete. This deviating behaviour will be discussed in addition to the behaviour of metals.

First of all the shock waves will be discussed and after that the elastic-plastic tension waves.

In a shock wave both a three-dimensional stretch as well as a tension situation occurs. The situation in a shock wave can however be very well approximated by assumption of a situation with one-axis deformation together with three-dimensional tension (this as opposed to the one-axis tension situation, with 1D tension and 3D deformation). This assumption of a one-axis deformation situation gives the advantage of a one-dimensional analysis.

The result of this assumption is that the material particles can only move in the direction of the shock wave. A material particle is supported by the material particles which surround it in the plane perpendicular to the propagation direction of the shock wave. All particles in this plane are in the same situation and can therefore also move in one direction. A situation of infinite support is therefore also spoken of.

Assume the theoretical case in which suddenly a pressure p_1 is applied to one of the two sides of a plate. This plate is made of compressible material and originally has a pressure of p_0 . The pulse arising here moves like a wave with velocity V_s . The pressure p_1 ensures compression of the material to a density of ρ_1 and simultaneously ensures a speeding up of the compressed material to a velocity of

- 25 -

u. Figure 3 shows a part of the material (standardized cross-section) with the normal in propagation direction.

5 The position of the front of the shock wave at a given moment is indicated by the line AA. A short time dt after that, the shock front has been moved to BB, whereas the material which was first situated on AA now has been moved to CC. The shock wave is therefore shown as a discontinuity. Despite this discontinuity the preservation of
10 mass, impulse and energy is still valid. In figure 3 it can be seen that the three balances are in balance:

$$\rho_0 V_s = \rho_1 (V_s - u) \quad \text{preservation of mass} \quad [4.1]$$

$$p_1 - p_0 = \rho_0 V_s u \quad \text{preservation of impulse} \quad [4.2]$$

$$15 \quad p_1 u = \frac{1}{2} \rho_0 u^2 + \rho V_s (E_1 - E_0) \quad \text{preservation of energy} \quad [4.3]$$

In which:

20 ρ_0, ρ_1 : density of the material before and after the front of the shock wave. (kg/m³)

p_0, p_1 : pressure in the material before and after the front of the shock wave. (N/m²)

E_0, E_1 : internal energy of the material before and after the shock wave (m²/s²)

25 V_s : velocity of propagation of the shock wave. (m/s)

u : velocity of the material (m/s)

Of these eight parameters it is assumed that ρ_0 , p_0 and E_0 are known so that five remain unknown. The behaviour of a
30 material around a shock wave can be determined by plotting two of the five variables (ρ , p , E , V_s , u) against each other. The curve created in this way is called the Rankine-Hugoniot, or Hugoniot for short. This curve is specific for a certain material, but by using various
35 parameters there are several possibilities to show the Hugoniot. Usually the Hugoniot is shown with the pressure as function of the density, the volume stretch or the

- 26 -

specific volume. The last two are derived from the density.

5 Assumptions which have been made in this derivation of the Hugoniot are: one-dimensional movement, thermodynamic balance before and immediately after the shock front and neglecting the strength of the material. The latter specifically goes for the shock waves with pressures which are far above the elastic limit: the material behaves like
10 a liquid without strength.

The Hugoniot is part of an "Equation of State" of a material. The Equation Of State (EOS) of a material gives the pressure as function of the density and the internal
15 energy, whereas in the Hugoniot the pressure is only a function of the density. The terms EOS and Hugoniot are often used one for the other, but this is only correct under special circumstances. In shock waves in solid substances and liquids the influences of the change of the
20 internal energy is small or negligible most of the time. The hydrostatic pressure p in a shock wave is only a function of the density then. This assumption results in the EOS and the Hugoniot being interchangeable. Further for the sake of clarity only the term Equation Of State
25 will be used.

From experimental examination it appeared that the EOS of most liquids and solid materials can be approximated by the following relation:
30

$$V_s = a + b u \quad [4.4]$$

The relation [4.4] indicates a quadratic relation in the tension-stretch diagram. The physical background of this
35 relation is not yet well understood.

The EOS of most materials can be indicated with the

- 27 -

relation [4.4]. Porous materials such as rock and concrete show a clear deviation. In figure 4 for concrete the hydrostatic pressure has been plotted against the relative volume change.

5

Above pressures of about 8 to 10 times the UCS the concrete starts to loose its internal strength. The cement matrix starts to pulverize. When the pressure increases the pores of the material will be compressed and the grains from which the material has been built will rearrange. When the material has been compressed completely the rigidity of the material will increase again. The rigidity of the grain material now is determinative.

15

The rigidity of the material and therefore the inclination in the tension-stretch diagram is responsible for the velocity of propagation of a shock wave. As can be seen in figure 4 a shock wave will deform as a result of the change in the inclination of the tension-stretch diagram. The shock wave will get an elastic precursor and a plastic part. Only with a shock wave with a very high tension (in this concrete over 30 GPa) one shock front will be formed.

20

Dry rock will show the same behaviour as the concrete in figure 4. In figures 5A, 5B, 5C and 5D some diagrams have been included in which the tension has been plotted against the specific volume. The diagrams contain the EOS of pure quartz, porous sandstone, pure calcite and porous calcite rock, respectively.

25

30

When there is water in the pores of the rock, the pores cannot be compressed completely: water is not as compressible as air. Whether the internal structure will crumble for a part is unknown. Examination will have to show what the EOS of a water-saturated rock will look like.

35

- 28 -

The intensity of an elastic-plastic tension wave is not as high as a shock wave's. The strength of the material now has an important contribution. The behaviour of elastic-plastic tension waves is therefore discussed on the basis of the strength of a material.

Often the strength of a material in the tension-stretch diagram is indicated with a one-axis tension curve as in figure 6. Said curve is obtained by means of a (static) triaxial test without support pressure. In figure 6 among others a curve of a elastic-perfect plastic material is drawn. Represented schematically many metals show such behaviour. The tension level in which the material changes from an elastic to a plastic behaviour, is indicated by the yield point or yield y_0 . For rock it goes that after reaching the maximum tension level, the UCS, more and more cracks are formed in the material, as a result of which the strength decreases.

As stated above, the situation in a tension wave can very well be approximated by assumption of a one-axis deformation situation. Said tension situation can be obtained by adjusting the support pressure in a static triaxial test such, that only stretch in axial direction can occur. The stretch in radial direction of the cylindrical test part is kept at zero (see figure 7).

In shock waves much larger tensions and stretch velocities often occur than can be obtained with a triaxial test. These large tensions and stretch velocities can be generated with a so-called "Plate Impact Test". In this test a missile is shot at a plate of the material to be tested. Plate impact situations by approximation create a one-axis deformation situation. The tension in a shock wave in which a material changes from an elastic to a plastic situation is called the "Hugoniot Elastic Limit" (HEL).

- 29 -

The characteristic tension-stretch curve for one-axis deformation situation of a metal is shown in figure 7, together with the corresponding EOS. The tension σ_1 as function of the stretch ϵ determines the tension situation in a shock wave.

For very high pressures ($\sigma \gg \sigma_{HEL}$) it can be seen that the difference $\sigma_1 - p$ is relatively small. The tension situation in the shock wave is then mainly determined by the pressure compression curve [$p = f(\Delta V/V)$], with $\Delta V/V$ the volume stretch. This is the EOS which has been discussed above. At very high pressures the material therefore behaves hydrodynamic (like a liquid). The tensions in all directions are equal to the hydrostatic pressure here.

At lower pressures the curve clearly deviates from the EOS. The elastic limit and therefore the strength of the material in this area has an important influence on the behaviour of the material.

In a elastic-perfect plastic material, the yield point or yield is independent from the pressure: $y = y_0$. The criterion describing this behaviour is the Von Mises criterion. Above the elastic limit of the material (the "Hugoniot Elastic Limit" or HEL) yielding occurs, the material plastically deforms. In a one-axis deformation situation, for an elastic-perfect plastic material with the Von Mises criterion, goes:

- * In the elastic area the modulus of the material is larger than in the plastic area.
- * In the plastic area the modulus is therefore equal to the modulus of the EOS.
- * In the plastic area the deviation of the largest main tension σ_1 to the EOS is constant.

The velocity of propagation of a tension pulse depends on the modulus, so on the inclination of the tension-stretch

- 30 -

curve. The result of this is that the elastic part of a shock wave propagates faster than the plastic part. A so-called "elastic precursor" with an intensity equal to σ_{HEL} occurs.

5

In figure 8 a load cycle can be seen. Relief in the first place occurs elastically. Not until after that does the plastic relief follow. A result of this is that at the tail of the pulse, where the relief occurs, a quickly propagating elastic relief wave overtakes a part of the plastic wave front. This can be seen in figure 9.

10

The strength of rock without support pressure is shown by UCS (see figure 6). With support pressure rock can absorb more tension. The support pressure ensures that rock will not fail until at much higher tensions. In figure 10 this can clearly be seen. The support pressure is shown with each tension-stretch curve.

15

The support that occurs in the one-axis deformation situation is also called infinite support. The strength of rock in this infinite support is also indicated by CCS (Confined Compressive Strength). Valid is:

20

$$CCS \approx 10 * UCS$$

25

Because of the large stretch velocities which occur in the shock waves, the strength will further increase. Valid is:

$$HEL \approx 1.5 - 2 * CCS \approx 15 - 20 * UCS$$

30

The values for CCS and HEL are based on experiments with hard rock such as granite. Because HEL has a great influence on the behaviour of an elastic-plastic tension wave, it is important that this parameter is known. Experimental tests will have to ensure this.

35

- 31 -

5 The Von Mises criterion for an elastic-perfect plastic material takes a constant yield point as starting point, independent from the prevailing pressure. This contrary to the Mohr-Coulomb criterion, which can be used for rock and concrete. In this criterion the yield point increases with increasing pressure. The sharp bend in the elastic limit in the tension-stretch diagram of figure 7 will make way for a gradual decrease of the inclination (modulus).

10 Later the differences between strength criteria and their influence on the behaviour of shock waves will be gone into.

15 In rock fracture is formed as a result of increase of the micro cracks which are already present in the rock. At the crack tips of these micro cracks tension concentrations arise. Tension concentrations may also arise along grains as a result of a difference in rigidity between grain and matrix material. In that way even in a tension situation in which on macro scale all main tensions are positive (pressure), cracks may yet increase on micro scale and the rock fails.

25 For a brittle material like rock it will be difficult to indicate what the load has to be for failure. This can, among others be made clear with the tension-stretch diagram with a one-axis tension situation (figure 3). The tension reaches a maximum: the UCS, but the rock can still absorb stretch after that before it has failed completely.

30 The same goes for the one-axis deformation situation in a shock wave. When the elastic limit (HEL) has been reached, the rock starts to plastically deform and cracks will start to grow. Whether an instable situation will arise, in which the cracks keep on growing until they reach a free surface or another crack, depends on the level and

35 the duration of the load. Below it is explained on the basis of the tension situation before and after failure,

- 32 -

how failure behaviour of a rock works.

5 The tension situation in a point in a material can very well be shown in the tension space (figure 11). Here the three main tensions are plotted along the axes. The tension situation somewhere in the material can now be indicated by a point $(\sigma_1, \sigma_2, \sigma_3)$ in the tension space. In the tension space the yield point can be drawn. In figure 11 this has been done for the Von Mises criterion (A) and 10 the Mohr-Coulomb criterion (B).

A point in the tension space can be built up from a hydrostatic part and a deviatoric part. Of the hydrostatic part the main tensions are equal to each other. For the 15 hydrostatic axis therefore $\sigma_1 = \sigma_2 = \sigma_3$ is valid. The deviatoric part of the tension will then become the deviation from this hydrostatic axis. In figure 11 the hydrostatic length ξ and perpendicular to it the deviatoric length ρ of a random point on the yield point 20 has been shown.

Above it was already mentioned that the yield point has a fixed value and that in the Mohr-Coulomb criterion the yield point depends on the prevailing hydrostatic pressure 25 $p(p = 1/3 (\sigma_1 + \sigma_2 + \sigma_3))$. In figure 11 this can simply be seen.

30 The tension situation is always situated on or within the yield point. When the difference between the main tensions is large enough the yield point is reached. When the largest main tension increases further material will yield. Here the smaller main tensions increase and as a result so will the hydrostatic pressure, so that the tension path will run along the yield point.

35 Rock has a strength behaviour which can be approximated with the Mohr-Coulomb criterion (figure 11(B)). Rock may

- 33 -

fail in the following three ways:

- 5 1. Failure as a result of shearing. As soon as a
tension situation arises which is on the yield point,
the rock will plastically deform. This will be accom-
panied by the growth of micro cracks. If this
situation will prolong long enough with sufficient
plastic deformation the rock will fail. In this way
10 the strength of the material will decrease down to a
residual strength of the material. This residual
strength can decrease here to a strength comparable
to the strength of sand. The areas in the material
which have failed will get a new yield point which is
closer to the hydrostatic axis.
- 15 2. Failure on traction. In figure 11(B) it can be
seen that the material has a limited strength when
the hydrostatic pressure is low. Below a certain
negative pressure the material will even have no
strength anymore. When the tensile strength is
20 reached then a traction crack will arise. In such a
location the material will be unable to absorb
negative tensions. Shearing and pressure tensions can
still be absorbed.
- 25 3. Failure on pressure. When the pressure tension
will become high enough, the rock will also fail on
the hydrostatic axis. The structure of the rock will
crumble and rock will pulverize. There is no univocal
criterion at hand from the literature which is ap-
plicable to this pulverization. Non-porous rock will
30 not fail until at very high pressures. The calcite
and/or quartz will first go through (several) crystal
phase changes.

35 Above-mentioned tension situations may occur both at the
cutting of rock and in shock waves. At cutting the rock
will pulverize around the tooth tip. Just outside the
pulverized zone the rock will fail as a result of

- 34 -

shearing. At a certain moment the tensile strength will be exceeded and from the sliding tension crack a traction crack will run to the surface. A fault block will break out as a result.

5

Also in explosions various failure areas can be found:

- 10 * Pulverization around the source of the load. Near the explosion the tension pressures are so high that this results in the destruction of the inter crystalline and inter granular structure.
- * Radial fractures around the pulverization zone. The shock wave will expand radially from the pulverization zone. This radial compression may generate traction tensions in the tangential direction.
- 15 * Spalling. As already mentioned above a traction wave may arise as a result of reflection of a pressure wave. This happens at reflection on a free surface or a boundary with a material with a smaller impedance ($\rho \cdot c$). Just after reflection, when the tensile strength is exceeded, a traction crack will arise.
- 20 This phenomenon is called spalling.

The above has made it clear that it is not simple to determine how a shock wave will propagate through a rock.

25 The problem will become even more difficult when the shock wave is situated in a spacial geometry. Because of the complexity it was decided to calculate the problem with an finite elements program. Such a determination will be advantageous when adjusting parameters in practical uses.

30

After a short description of the program AUTODYN TM a one-dimensional simulation with a linear elastic material is started with. Step by step the problem is made more complex into a two-dimensional simulation in which the

35 material has a strength and a failure model. At the end of this paragraph the influence of some parameters on the shock propagation and the simulated breaking behaviour

- 35 -

will be examined.

AUTODYN TM is a program (so-called "hydrocode") of Century Dynamics Inc. which has especially been designed for non-linear dynamic problems. The program is especially used for problems which strongly depend on time which are geometrically non-linear (large stretches) and in which the material behaves non-linear (plasticity and failure). These are particularly impact and penetration problems (ballistics), the simulation of explosions and the examination of shock waves in gasses, liquids and solid materials.

Both time and space are divided by AUTODYN. The time is divided in steps in time and the space into cells. Each step in time the program calculates the set of cells. The outcome of such a calculation cycle is the starting point of a next cycle.

For solving a problem AUTODYN can make use of different numerical processors. The most important are the Lagrange and the Euler processors. With the Lagrange processor the material is divided into cells in which the vertices remain attached to the material, no material is moved through the cell boundaries. Because the cells deform with the material, this model is suitable for solid materials.

In the Euler processor the vertices of the cells are attached to the space and the material flows through these cells. This processor is particularly suitable for gasses, liquids and very large deformations of solid substances. In very large deformations Lagrange will become inaccurate and (part of) the problem will have to be checked with Euler. For complex problems AUTODYN can couple both processors.

For this problem the Lagrange processor has been chosen,

- 36 -

so that the deformation of the rock can be followed well. During the simulations it appeared from the deformations that there was no reason to run a check with the Euler processor.

5

The following actions have to be taken in setting up a new simulation:

* making grid

10

AUTODYN can in a simple manner divide the system, which has to be calculated, into finite elements, also called cells. AUTODYN only counts in quadrangular cells. Each cell has four nodal points and the four sides of the cell consist (also after deformation!) of straight lines. The set of cells is also

15

called the grid.

* filling the grid with material

20

The cells can now be filled with a material. For each material data have to be given about the EOS, the strength criterion and the failure model. These material models are elucidated hereafter.

* initial conditions

It should be indicated what the point of departure is on $t = 0$: indication of initial velocity, tension or energy of a material.

25

* indicating boundary conditions

Boundary conditions can be imposed on the sides of the cells, in which the boundary condition is constant between two indicated nodal points. Examples of boundary conditions are: a certain course of the tension in the time, velocity in x- and y-direction or transmitting tensions out of the system.

30

* indicating targets

In the grid targets can be placed. These targets register the changes in the time of each wanted variable. In this way after the simulation ends the history of the various points in the system can be shown.

35

* symmetry

With AUTODYN a situation can be calculated in which the cells are infinite long in the direction perpendicular to the 2D surface. A second possibility is a rotation-symmetric situation, in which the x-axis is the axis of symmetry. In this way annular cells are created: a cell is a body of revolution with a quadrangle as surface of revolution.

The 1D sum is built up as follows (see figure 12): One row of cells, 2.5 cm of water, 10 cm of rock and 5 cm of gravel. In order to create a 1D situation, a velocity zero in y-direction is imposed on the upper and lower side of all cells. In this way a one-axis deformation situation is realized which realistically corresponds to the actual situation in a plane-shaped wave front. Here material particles in directions perpendicular to the propagation direction of the wave are supported by surrounding material particles which are in the same situation: the material particles can only move in the direction of the propagation direction of the wave.

In the first sum the rock is regarded as a linear elastic material. In order to compare this simulation with the analytical sum of chapter 3 the same material characteristics are chosen:

	water	rock	gravel
EOS	linear	linear	linear
K (GPa)	2.3	12.7	4
ρ (kg/m ³)	1000	2500	2000
Strength	none (hydro)	elastic	none (hydro)
G (GPa)	--	7.6	--

Table 2: material characteristics of the linear elastic

simulation.

On the left hand side of the first cell (water) a square-shaped tension pulse is put: 100 MPa during 10 μ s. The water has no strength and therefore has a yielding behaviour. This results in all tensions being equal to the hydrostatic pressure:

$$\sigma_1 = \sigma_2 = \sigma_3 = p = 100 \text{ MPa}$$

This pulse has a velocity of

$$c = \sqrt{\frac{K}{\rho}} \approx 1500 \text{ m/s}$$

On the boundary surface water-rock a part of the pulse is reflected and a part enters the rock layer. With the impedance ($c \cdot \rho$) of both materials the transmission and the reflection coefficients can be determined (see equation [3.5]). Here is valid: $R = 0.64$ and $T = 1.64$ for the amplitude of the tension pulse. The amplitude of the largest main tension σ_1 , the direction which corresponds to the propagation direction of the elastic wave in this way becomes:

$$\sigma_{1r} = T \times \sigma_{1w} = 164 \text{ MPa}$$

The other two main tensions σ_2 and σ_3 can be derived by applying the Law of Hooke for the space tension situation:

$$\varepsilon_x = \frac{1}{E} (\sigma_x - \nu \sigma_y - \nu \sigma_z) \quad [6.1]$$

$$\varepsilon_y = \frac{1}{E} (-\nu \sigma_x + \sigma_y - \nu \sigma_z)$$

$$\varepsilon_z = \frac{1}{E} (-\nu \sigma_x - \nu \sigma_y + \sigma_z)$$

The inverse form of [6.1] reads:

- 39 -

$$\sigma_x = \frac{E}{(1+\nu)(1-2\nu)} \{ (1-\nu) \varepsilon_x + \nu \varepsilon_y + \nu \varepsilon_z \} \quad [6.2]$$

$$\sigma_y = \frac{E}{(1+\nu)(1-2\nu)} \{ \nu \varepsilon_x + (1-\nu) \varepsilon_y + \nu \varepsilon_z \}$$

$$\sigma_z = \frac{E}{(1+\nu)(1-2\nu)} \{ \nu \varepsilon_x + \nu \varepsilon_y + (1-\nu) \varepsilon_z \}$$

These equations are also valid for the three main tensions $\sigma_1, \sigma_2, \sigma_3$. Furthermore the one-axis deformation situation has been assumed for this 1D situation: $\varepsilon_y = \varepsilon_z = 0$.

In this way follows:

$$\frac{\sigma_2}{\sigma_1} = \frac{\sigma_3}{\sigma_1} = \frac{\nu}{1-\nu} = \frac{1}{3}$$

5 with $\nu = 1/4$ (general assumption for rock)

Therefore for the tension in the two main directions follows $\sigma_2 = \sigma_3 = 1/3 \sigma_1 \approx 53$ MPa.

10 By definition the hydrostatic pressure p is the average of the three main tensions:

$$p = 1/3 (\sigma_1 + \sigma_2 + \sigma_3) \quad [6.3]$$

15 with $\sigma_2 = \sigma_3 = 1/3 \sigma_1$ this will become:

$$p = \frac{1}{3} \left(\frac{5}{3} \sigma_1 \right) = \frac{5}{9} \sigma_1 \approx 90 \text{ MPa}$$

The same sums can be made for the transition rock-gravel. The outcome of these are:

20 For the reflected wave in the rock: $\sigma_1 = -70$ MPa; $\sigma_3 = 1/3 \sigma_1 = -23$ MPa

For the transmitted wave in the gravel: $\sigma_1 = 97$ MPa.

The above-mentioned values of tensions can be read in

- 40 -

figure 13. Here the tensions are plotted against the time for various targets.

5 It can be seen that the elastic wave deforms while it goes through the water, the rock and the gravel. In a pure elastic wave with a pure one-dimensional propagation, there is no deformation. A rectangular pulse with infinite steep inclinations, in theory keeps its shape. The deformations which can be seen, the rounding-off of the rectangular pulse and the changes of the inclinations, are a result of numerical inaccuracies. The degree of deformation can be limited by choosing a finer grid (more cells). The inclination of the pulse can be used as measure for the accuracy. The amplitudes remain constant
10 indeed as long as the pulse remains in one particular medium.
15

The outcome of these numerical elastic sum, leaving the deformations of the pulse aside, correspond to the outcome of the analytical sum.
20

In the first simulation described above the rock behaved elastic. This behaviour, however, is only valid in tensions below the elastic limit of the material. Above said limit the rock will plastically deform and starts to fail.
25 In other words: rock has a certain strength. AUTODYN has various models available to simulate the strength of a material. First the Von Mises criterion was used. After that the Mohr-Coulomb will be discussed.
30

The material characteristics in these simulations are chosen such that the various material models can be well compared to each other. Differences between the various material models should be apparent more clearly. Not until
35 later in this chapter, when the choice for the material models has been made, will all material characteristics be determined carefully as well. Finally, in the two-dimen-

- 41 -

sional simulations, the material characteristics will in value differ less than 30% from the values used in these one-dimensional sums. The load remains a square-shaped pulse of $10\mu\text{s}$; the amplitude is 1 GPa, well over the elastic limit.

The characteristics for water and gravel remain the same as in the elastic sum. For rock now goes:

EOS	linear
K (GPa)	12.7
ρ (kg/m ³)	2500
Strength	Von Mises
G (GPa)	7.6
y_0 (MPa)	200

Table 3: chosen material characteristics of the rock with Von Mises strength criterion.

With the Von Mises strength criterion plastic yield behaviour of materials can be described in a simple manner. The only material constant besides the shearing modulus that has to be entered, is the one-axis yield point or yield y_0 . The influence of this criterion can be seen in the tension-stretch diagram of figure 4, 6 and 14A, 14B, 14C. A clear bend can be seen in the elastic limit. In the plastic area a lower bulk modulus is valid and therefore also a lower propagation velocity of the plastic part of a shock wave. The higher velocity of the elastic part of a shock wave results in the formation of an "elastic precursor". A wave with a tension equal to the elastic limit precedes the plastic wave.

In figure 14, in which for target 5 the tension σ_1 ($= \sigma_x$) has been plotted against the compression (volume stretch),

- 42 -

it can be seen that with the indicated yield point $y_0 = 200$ MPa an elastic limit $HEL = 300$ MPa follows (which besides on y_0 also depends on ν).

5 At first relief takes place elastically. Only after that
does the plastic relief follows. A result of this is that,
at the tail of the pulse, where relief takes place, a
rapidly propagating elastic relief wave, depending on the
length of the way, overtakes a part of the plastic wave
10 front.

In figure 14 the results are included of the elastic-
plastic sum of the Von Mises Criterion. In the plot, where
the course of the largest main tension (σ_x) has been shown
15 in the time for various targets, the following strikes:

- * The tension course of target 3 (the first target in
the rock) as far as shape and intensity is concerned
looks like an elastic wave (about 1.6 times the pulse
in the water).
- 20 * As the pulse goes further through the rock it
deforms.
- * The front of the wave splits into an elastic and a
plastic part. The elastic part has a higher
propagation velocity.
- 25 * The pulse is topped off, the elastic relief wave
overtakes a part of the plastic wave front. The top-
ping-off is complete after approximately 6 cm rock
(between target 5 and 6).
- * The basis of the pulse becomes wider.

30 In the plot in which for target 5 p, σ_x and σ_y have been
plotted against the time, it can be seen that the elastic
part, which starts at approximately $25\mu s$, complies with
the elastic calculation rules that have already been
35 mentioned before: $\sigma_y = 1/3 \sigma_x$ and $p = 1/3 (\sigma_x + \sigma_y + \sigma_z)$.
Furthermore it can be seen that for the plastic part goes
that the tensions are almost equal to each other. Yielding

clearly occurs.

5	The material characteristics are chosen as follows:	water	rock	gravel
	EOS	linear	linear	linear
	K (GPa)	2.3	12.7	4
	ρ (kg/m ³)	1000	2500	2000
10	Strength	none (hydro)	Mohr-Coulomb	Mohr-Coulomb
	G (GPa)	--	7.6	0.1
	y in p=-1MPa	--	0	0
	y in p= 0MPa	--	10 (MPa)	0
15	y in p=100MPa	--	100	200
	y in p=1GPa	-	316	2000

Table 4: Material characteristics in the simulation with the Mohr-Coulomb strength criterion.

20

In the Mohr-Coulomb model four points from the relation y-p have to entered. It can clearly be seen that with lower pressures the yield point y is quite lower than with higher pressures. This is contrary to the Von Mises criterion, in which the yield point is constant regardless of the pressure. This difference can clearly be seen in the tension-stretch diagram (figure 4, 15A, 15B and 15C). The sharp bend in the Von Mises criterion makes way for a gradual decrease of the inclination (modulus). Furthermore it can be seen that the elastic relief is larger than in the Von Mises criterion. The results of this can clearly be seen in the plot in which the tensions of target 5 are

30

- 44 -

plotted against the time:

- * The elastic precursor can be seen less clearly than in Von Mises.
- 5 * The decrease in intensity as a result of elastic relief is larger than in Von Mises.

The Von Mises criterion gives a realistic approximation of the behaviour of most metals. The behaviour of rock, concrete and soil is usually indicated with a failure curve, such as is described. Often failure curves are indicated in a Mohr-diagram, in which the sliding tension is plotted against the standardized tension. Under these failure curves circles of Mohr can be drawn. From these failure curves it clearly appears that the yield point depends on the prevailing pressure. For that reason the Mohr-Coulomb strength model is chosen to model the yield behaviour of rock in AUTODYN.

20 The failure curve according to the Hoek & Brown criterion approximates the behaviour of rock realistically. This criterion is based on the area with low support pressure where brittle fracture occurs. The criterion reads:

$$\sigma_{1n} = \sigma_{3n} + \sqrt{m\sigma_{3n} + s} \quad [6.5]$$

in which:

- 25 σ_{1n} : the standardized largest main tension $\sigma_1/\text{UCS (MPa)}$
- σ_{3n} : the standardized smallest main tension $\sigma_3/\text{UCS (MPa)}$
- m : constant depending on the type of rock $m = \text{UCS/TS}$
- s : the fracture degree of rock. ($s = 1$ for crackless rock, otherwise $s < 1$)

30 The Mohr-Coulomb strength model requires a relation between the yield point y and the hydrostatic pressure p . Generally the following relation is stated for the yield point:

$$35 \quad 2(y)^2 = (\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \quad [6.6]$$

- 45 -

When the 1-direction the propagation direction of the shock wave is taken, σ_1 is the largest main tension. Additionally it can be simplified by stating that $\sigma_2 = \sigma_3$. This assumption is true for 1D sums. For 2D rotation symmetrical sums this is a good approximation. Now follows:

$$y = \sigma_1 - \sigma_3 \quad (\text{with } \sigma_2 = \sigma_3 \text{ and } \sigma_1 > \sigma_3) \quad [6.7]$$

In the science of rock often the parameter q is used in [6.7]: $q = \sigma_1 - \sigma_3$. The definition of p [6.3] becomes:

$$p = 1/3 (\sigma_1 + \sigma_2 + \sigma_3) = 1/3 \sigma_1 + 2/3 \sigma_3 \quad [6.8]$$

When [6.7] and [6.8] are substituted in [6.5] this results in:

$$\frac{y}{UCS} = -\frac{1}{6}m + \sqrt{\frac{1}{36}m^2 + \frac{p}{TS} + 1} \quad [6.9]$$

In the basic model UCS and TS, 10 and 1 MPa, respectively, are taken. This results in a value of $m = 10$.

The Mohr-Coulomb strength model in AUTODYN requires the entering of four points from the relation y - p . In figure 16 the relation [6.9] has been shown in addition to the entering of the Mohr-Coulomb strength model.

The four points which have been entered in the Mohr-Coulomb strength model comply with the relation [6.9]. These are:

p (MPa)	-1	10	100	1000
y (MPa)	0	20.5	85.2	300

Table 5: entering of the Mohr-Coulomb strength model: four points in the relation y - p .

- 46 -

As already mentioned the Hoek&Brown criterion is based on test pieces which have failed brittle. In figure 16 the brittle-plastic separating line as been included. On the right hand side of the separating line the rock will plastically fail. The curve and the two points in this area have been extrapolated and therefore are less reliable than the two points in the brittle area on the left hand side of the separating line.

In words this strength model comes down to that at a certain pressure p the difference between two main tensions cannot become larger than the value of the yield point y belonging to that pressure. When the yield point is reached a rise of the largest main tension automatically results in the other main tensions rising along. The tension situation can then be found back on the failure curve at a higher pressure.

AUTODYN has various models available for the EOS of a material. For solid and liquid materials the linear EOS and the Shock EOS are applicable. Additionally there is the possibility to model porous materials. The models for gasses are left aside here.

The most simple EOS is the linear EOS. Here the Law of Hooke is the starting point:

$$p = K\mu$$

$$\text{with } \mu = (\rho/\rho_0) - 1 = \Delta V/V$$

This model therefore only requires the bulk modulus K and the initial density ρ_0 . In the determination of the density and the bulk modulus of the rock material the characteristics of the main components have been taken as starting point. Because no data are available on the characteristics of the water-saturated rock, K and ρ_0 are calculated with the density and the bulk modulus of the components

- 47 -

calcite, quartz and water. The composition of rock has been derived from the material examination. Further it has been assumed that with UCS = 10 MPa the porosity $n = 20\%$. The composition and the characteristics of the components have been chosen as follows:

component	volume per-centage	K (GPa)	ρ (kg/m ³)
calcite	52%	73	2775
quartz	28%	38	
water	20%	2.3	1000

Table 6: The composition and the characteristics of the components of the rock material.

The density of the grain material comes from the material examination. Here one average density for the grain material has been assumed. The total density for the water-saturated rock will then be:

$$\rho_0 = n \times \rho_w + (1-n)\rho_s = 0.2 \times 1000 + 0.8 \times 2775 = 2420 \text{ kg/m}^3$$

The bulk modulus K can be calculated by assuming that the separate components cooperate as three parallel springs. The bulk modulus can then be calculated with the volume percentage and the bulk modulus of each separate component:

$$\frac{1}{K} = \sum_i \frac{\alpha_i}{K_i} \quad [6.10]$$

in which:

K : the bulk modulus of the total material (N/m²)
 α_i : the volume percentage of a component (-)
 K_i : the bulk modulus of said component (N/m²)

- 48 -

Equation [6.10] strongly resembles the equation of Gassmann [3.4]. When the bulk modulus of the rock in the drained situation K_0 is neglected both equations are equal to each other. The drained bulk modulus has little influence in equation [3.4] and will moreover fail above the elastic limit.

With [6.10] follows:

$$\frac{1}{K} = \frac{0.52}{73} + \frac{0.28}{38} + \frac{0.2}{2.3}; \quad K \approx 10 \text{ GPa}$$

As mentioned above, the EOS of most liquids and solid materials can be approximated by the equation [4.4]:

$$V_s = c_0 + su$$

in which:

V_s : propagation velocity of a shock wave (m/s)
 c_0 : the velocity of sound (m/s)
 s : a material constant (-)
 u : velocity of material (m/s)

Due to lack of data on water-saturated rock it is impossible to use this approximation of the EOS.

AUTODYN, besides the above-mentioned models, has the possibility to model porous materials. Materials such as rock, concrete and sand contain pores, which under pressure of for instance a shock wave can crash. In the porous model the pressure can be entered lineary step by step as a function of the density. In that way the three areas of elastic compression of the intact material, compaction by failure and compression of the condensed material can be modelled.

Water-saturated rock as a result of the presence of water in the pores cannot be condensed completely. The modelling of water-saturated rock by means of the porous model

- 49 -

therefore does not appear to be correct. Again due to the lack of data this model cannot be used.

From the limited data available on the EOS of dry rock without pores it follows that with pressures in the range from 0 to 2 GPa the EOS can be approximated by a straight line. For that reason and because of the lack of data on water-saturated rock the linear EOS has been chosen. It is expected that the water in the pores ensures that the components from which the material has been built up cooperate like parallel springs. The rock is now presented as a homogeneous material with a new bulk modulus determined from the components from which the rock has been built up.

Experimental material examination is necessary to determine the behaviour of water-saturated rock under shock load with pressures between 0 and 2 GPa. The Plate Impact Test or the Hopkinson Bar Test could be used for this examination.

For the elastic and the elastic-plastic sum with Mohr-Coulomb the total energy of the system has been plotted against the time in figure 17A and 17B. During the first 10 μ s the square-shaped pulse is put on the water and the energy rises. A part of the pulse will reflect against the boundary water-rock. The boundary condition of the first cell has been chosen such that all tensions and energy is transmitted out of the system (boundary condition "transmit"). In the energy plot it can therefore be seen how much energy is reflected against the boundary water-rock. This is the first decrease of the total energy. Later yet another part of the energy will leave the system through the last gravel cell, which also has the transmit boundary condition.

The reflected wave against the boundary water-rock in the

- 50 -

elastic sum contains about 37% of the incoming wave. This produces an energy transfer of about 63%. In the elastic-plastic sum this is considerably higher, about 88%. The energy transfer is better when there is yield.

5

With the one-dimensional simulations a good view has been obtained of the propagation of a shock wave. Various characteristics such as EOS and the strength of a material have been discussed. With the insight obtained a subsequent step can now be taken and the problem be made more complex. The three-dimensional problem is rotation-symmetric so that a two-dimensional geometry will suffice.

10

As described above the rock may fail on traction, by shearing and pulverization on pressure. AUTODYN has various failure models available which can model the failure behaviour:

15

* Maximum traction tension of the main tensions. When one of the three main tensions exceeds the indicated traction tension the material fails and can subsequently only absorb positive tension. This criterion is suitable for modelling failure on traction of rock (see figure 16).

20

* Maximum sliding tension. Above a certain indicated maximum sliding tension the material fails (see figure 16). The maximum yield point and with it the sliding tension in rock depends on the prevailing pressure. This model therefore cannot be used.

25

* Maximum value of the main stretches (on traction). The rock fails when it is stretched too far in one of the directions of the main stretches. There are no direct data available for this criterion.

30

* Maximum sliding stretch. The rock fails when it shears too much. Just like the sliding tension with rock it depends on the prevailing pressure and therefore cannot be used.

35

* Direction depending maximum traction tension or

- 51 -

stretch. This model is suitable for materials with direction depending characteristics (orthotropic materials).

5 * Damage model depending on plastic stretch on pressure. This model calculates with a damage parameter $D=0$ for intact rock and D_{max} (<1) for failed rock. The value of D depends on the plastic stretch. The rock starts to fail as of a certain compression. The yield point and the bulk modulus decrease under the influence of D . This model is suitable for the simulation of the pulverization on pressure. However, there are no data available for a good estimate of the plastic stretch.

10 * The Johnson Holmquist model. This model also works with a damage parameter. For $D=0$ a failure curve is valid as with the Mohr-Coulomb criterion. For maximal failed rock the failure curve is valid which indicates the residual strength (see figure 16). This model appears to be very suitable to simulate both failure on traction and on shearing. During this examination, however, this model was not available yet. For future simulations this model appears to be suitable.

25 In figure 18 three of the above-mentioned failure criteria are indicated in a p-y diagram.

30 As appeared from the above-mentioned enumeration of the failure criteria available, only the criterion for the maximum tensile strength could be used. A maximum value of 3 MPa was chosen which one of the three main tensions may reach. In figure 11B it can be seen that one of the three main tensions can reach the maximum value, or all three at a time along the hydrostatic axis.

35 The model for the two-dimensional rotation-symmetric simulations is described here on the basis of the used

- 52 -

grid, the material models and the load.

The grid model which has been taken as starting point for the 2D sums has the following characteristics (see figure 19 and 20):

- * rotation-symmetry about the x-axis (lower side), this gives annular cells.
- * Thickness of rock layer 10 cm, thickness of gravel layer 5 cm.
- * Radius of the grid 35 cm.
- * Boundary condition at the lower side of the gravel and at 35 cm from the axis of symmetry (upper and right hand side in figure 19) is "transmit": tensions are transmitted out of the system, nothing is reflected.
- * The total grid consists of 1750 cells.
- * At the side of the load (left hand side in figure 19) cells are more finely divided, because there the largest tensions and deformations can be expected.
- * The targets, the places of which after the simulations have ended, the history of the load can be examined are divided as indicated in figure 20.

The following material characteristics have been used:

Rock:

- * Linear EOS
- * $K = 10 \text{ GPa}$; $\rho_0 = 2420 \text{ kg/m}^3$; $G = 6 \text{ GPa}$.
- * Mohr-Coulomb strength criterion (choice strength criterion)
- * Failure model: maximum main tension on traction of 3MPa

Gravel:

- * Linear EOS
- * $K = 5.9 \text{ GPa}$; $\rho_0 = 2072.5 \text{ kg/m}^3$; $G = 0.5 \text{ GPa}$.
- * Mohr-Coulomb strength criterion

- 53 -

* no failure model

On the basis of the calculations according to the above discussion a rock layer can apparently be crushed by a shock wave which ensured a load with an annular geometry. Starting point is an annular wire (through which an electric pulse is sent) which explodes 2 cm above the rock layer. The ring has a radius of 20 cm.

The explosion apparently can ensure a load which is distributed over an area of 4 cm wide. The load can only be applied constantly over a width of a cell. A stepped course (see figure 19) was chosen with a maximum tension (0.7 GPa) on a radius of 20 cm.

Further starting points of the load are:

- * A triangular shape of the pressure course in the time of the shock wave. The front of the shock wave is infinite steep here.
- * The duration of the shock wave is 25 μ s.

The effects the shock wave has on the rock and the gravel will be discussed here in chronological order. In figures 21A up to and including P can among others be seen:

- * The course of the pressure p in the rock and the gravel, every twentyfifth step in time.
- * The course of the pressure p in the time for a number of targets.
- * The situation in which the material is: elastic, plastic or failed in one of the three directions.

As can be seen in figure 21 the tensions in the rock near the load are high. The shock wave has the shape and the intensity of the load imposed. The tension in all directions is well above the elastic limit (see pressure course target 1). Still, it is possible that on micro scale

- 54 -

traction tensions arise along the grains or in crack tips already present. As already mentioned before the rock can fail in this way.

5 After $25\mu\text{s}$ the total load in the shape of a triangular pulse has been supplied to the rock layer. As of this moment traction tensions arise at the tail of the shock wave. These traction tensions arise at the edges of the location where the load of 4 cm in width has been put on.
10 The cause of these traction tensions can clearly be seen in the (enlarged) velocity plot on step in time 50. The rock particles move away from the location of the load. The shock wave experiences a lot of resistance of the rock at the centre below the location of the load. The free
15 rock surface does not offer that resistance. The rock particles tend to splash away. In reality this will probably happen too.

In the enlarged situation plot of step in time 50 the
20 directions of the main tensions have also been indicated. It can clearly be seen that below the location where the load has been put on, the main tensions lie along the x- and y-axis. Here the largest main tension is directed along the x-axis. Outside the area where target 1 up to
25 and including 9 lie the directions diverge from the x- and y-axis. The largest main tension turns from the x-axis to the y-axis. This pattern of directions can also be seen with the traction cracks which arise in this area. These will, as seen from the location where the load was on, run
30 away radially.

After approximately $40\mu\text{s}$ the shock wave reaches the boundary with the gravel. As of this moment a part of the shock wave will continue in the gravel layer, the other
35 part will reflect like a pulling wave. The front of the reflected part will at first fall away against the tail of the incoming shock wave. In figure 21 it can be seen in

- 55 -

the pressure course on step in time 100 that at about 2 cm from the boundary surface the pressure has become negative. In the situation plot of said same enclosure it can be seen that on that location the tensile strength of the rock has been reached. At this location a crack will arise. The distance from the boundary surface where this is happening depends on the difference in impedance between both materials, the course of pressure of the tail of the pulse and the tensile strength. This phenomenon is also called "spalling".

In the general case of an increasing shock wave it decreases in intensity in two ways. First of all the material will plastically deform or fail. Energy of the shock wave is transformed in deformation energy. Secondly the energy of the shock wave will be distributed over an ever larger area. The latter can therefore also be called the "geometric evaporation" of a shock wave.

With an annular load the geometry of the load will however ensure a reinforcement. To the outside, away from the axis of symmetry, the intensity of the shock wave indeed decreases, but within the ring as the energy of the shock wave as it increases in the direction of the axis of symmetry, will be distributed over an ever smaller area. As a result the intensity of the shock wave increases. With an annular load geometric reinforcement therefore occurs.

Around the axis of symmetry the geometric reinforcement described above arises. On step in time 175 it can be seen that traction tensions arise. Behind the pressure wave a traction wave arises, as a result of which the rock will fail near the axis of symmetry.

The concentrated pressure wave on the axis of symmetry will partly reflect against the rock-gravel boundary

- 56 -

surface here as well. Said reflection causes the formation of a second "spall" area.

All above-mentioned areas where it can be expected that the rock will fail are shown in figure 22.

1. Zone where pulverization can be expected. (not simulated)
2. Radial cracks as seen from the crater.
3. Spalling as a result of reflection against the boundary rock-gravel.
4. Traction cracks as a result of a traction wave near the axis of symmetry.
5. Spalling as a result of reflection near the axis of symmetry.

The main object of this examination is determining the quantity of energy necessary to crush a rock layer efficiently with a shock wave. The pieces that are realized may not be larger than 10 cm.

For an estimate of the size of the pieces with the help of the results and particularly the above described failure pattern, the important question is: How far has the rock disintegrated in the areas which according to the simulation have failed. Two extremes are possible:

1. In areas which according to the simulation have failed only some cracks have formed. The cracks run through the heart of these areas. See figure 23.
2. The areas where the rock has failed are completely pulverized down to the grains from which the rock was originally built up.

In the first case pieces will be formed which are larger than 10 cm. Pieces of about 15 cm appear to be possible. The hole which is formed moreover has a radius of merely 40 cm.

- 57 -

In the second case, taking the maximum distance between the failed areas into account, pieces of about 5 cm are possible (figure 21, situation plot step in time 275). Theoretically annular pieces could be formed. However, this does not seem to be likely. The hole that is formed has a diameter of about 55 cm.

Validation of these simulation with experiments is necessary to show how the rock fails exactly and which failure pattern goes with it. With the results of this simulation as only information, the maximum size of piece can be estimated at about 10 cm.

In the energy plot of figure 24 it can be seen that as a result of the annular load approximately 29 kJ is supplied to the rock. Furthermore it can be seen that merely 10% (± 3 kJ) goes into the gravel. In order to get 29 kJ into the rock, however, a larger quantity of energy is necessary in the wire. The energy which is released at exploding the annular wire, will, because of the shock wave which is caused, spread in all directions. Only a part of the energy will penetrate the rock layer. Half the energy has the wrong direction and will never reach the rock layer. Another part will be reflected against the boundary water-rock.

When it is assumed that a quarter of the energy released at the explosion of the wire penetrates the rock layer, about 120 kJ is necessary in this method, to obtain pieces of maximally 10 cm in a rock layer of 10 cm in thickness. Here the rock has the material characteristics as shown in figure 19. With the pulverized volume of 0.02 m³ the specific energy of this method can be estimated at:

$$SE \approx 6 \text{ MJ/m}^3$$

This value matches the estimates given above very well.

- 58 -

Here it is then assumed that a mere 1.5 MJ/m^3 enters the rock (a quarter). Experimental examinations will have to prove whether this is a correct assumption.

5 Directly below the explosion the transfer of water to rock is exactly like in the one-dimensional situation. From the results of the 1D sum with the Mohr-Coulomb criterion, a tension ratio of the incoming and transmitted wave of 1.6 followed. For a load of 700 MPa on the rock layer a shock
10 wave in the water of $700/1.6 \approx 440 \text{ MPa}$ is therefore necessary. This means that with a distance of 2 cm between the wire and rock the shock wave must still have an intensity of 440 MPa left. The duration of the pulse here remains $25 \mu\text{s}$.

15 In the energy plot of figure 24 it can be seen that the largest part of the added energy is transformed into deformation energy. Deformation energy here means the energy which results both in change of volume and change
20 of shape. The largest deformations occur near the annular load. In this zone the largest part of the energy of the shock wave is absorbed. This can also be noticed from the large decrease of the intensity of the shock wave in this area (figure 21, σ_1 and p plotted against time for various
25 targets).

A shock wave with a low intensity and a long duration of pulse will have rock fail over a larger area than a shock wave with a large amplitude and a short duration of pulse.
30 Here the intensity of the shock wave has to be well above the elastic limit of the material.

An important parameter with which the load can be changed is the radius of the exploding wire. From the results of practical tests it appears that the rock has mainly failed
35 within a radius of 25 cm. The cause of this is the already discussed geometric reinforcement towards the axis of

- 59 -

symmetry and the geometric evaporation outside of it. Furthermore it strikes that the rock in the area with a radius between 5 and 15 cm contains fewer cracks. This failure pattern is important in the choice of the radius of the load.

Before the simulation with the basic model was carried out, two simulations have been carried out with as deviating failure criterion a maximal traction tension in the main directions of 10 MPa instead of 3 MPa as in the basic model. The radius of the load in one of these two simulations was 10 cm, in the other simulation 20 cm, as in the basic model. The amplitude of the load is adapted such, that at the same duration of pulse of 25 μ s, the energy supplied was about the same. A stepped load was taken here, with 1.3 GPa as highest tension (as opposed to 0.7 GPa for the load at 20 cm). In figure 25A and 5B it can clearly be seen that with a radius of load of 20 cm the rock fails less quickly as a result of a heavier failure criterion. Still the five separate areas of figure 22 can be seen here as well. At a radius of the load of 10 cm the following strikes:

- * A larger crater is formed. Because of the larger intensity of the load the deformations in the surroundings of this load are larger too.
- * Despite the heavy failure criterion the rock almost completely fails within a radius of 12-15 cm.
- * Also with this heavy failure criterion there is no reason to assume that with this radius of load the rock fails up to a radius of 25 cm.

Regarding the choice for the radius of load the following can be said:

- * At too small a choice of the radius of load, too small an area is covered.

- 60 -

- * At too large a radius of load there is a chance that the rock only fails in the area below the load and near the axis of symmetry. The pieces which are formed between these areas can become too large.
- 5 * When it is desired that an area with a radius of 25 cm fails, a radius of the load of 20 cm appears to a good choice.

10 Furthermore it can be stated that the annular exploding wire appears to be an effective way to apply a quantity of energy over a large area in an distributed manner.

15 In the plot of figure 21, where the pressure p for various targets has been plotted against the time, a wavy movement or bend of the pressure after the maximum pressure in a target has been reached, strikes. The wavelength of this bend appears to be about 2 cm, whereas the cells are about $\frac{1}{2}$ cm long.

20 By halving the size of the cells (four times as many cells) the influence of the choice of grid on the results has been worked out. The plots going with this simulation have been included in figure 26A up to and including C. AUTODYN automatically determines the necessary step of
25 time for each calculation cycle. This is equal to the time needed by a sound pulse to go through a cell. The finer the grid, the more steps in time and thus the longer the calculation time. The simulation was broken off after $60\mu s$ (350 steps in time), because all the necessary information
30 had been obtained.

It can be seen that the bend has become smaller. The wavelength now is 1 cm. Therefore there is a clear connection between the size of the cells and the bend (accuracy).
35 Furthermore it can be seen that the same areas fail as in the basic model. The same failure pattern can be seen (the shock wave has not yet reached the axis of

- 61 -

symmetry at 60 μ s). It can be concluded that the grid of the basic model is sufficiently accurate. The size of the cells here are approximately $\frac{1}{2} \times \frac{1}{2}$ cm.

5 The thickness of the rock layer will in reality not be constantly 0.1 m. For that reason it has been worked out with a simulation what happens to the shock wave and the rock, when 0.2 m is taken as the thickness. In figure 27A-G the results can be seen. The same failure areas as in
10 figure 22 can be seen. Striking is the large area where spall occurs (areas 3 in figure 22). A possible cause of this is the angle of incidence of the shock wave.

15 When a shock wave meets a boundary surface with another material, then beside the material characteristics of the two materials also the angle of incidence is determining of how much is reflected and how much goes through. If the direction of propagation of the wave is perpendicular to the boundary surface, the transmission is largest. The
20 farther the direction of propagation diverges from the normal, the more energy reflects. Over a certain diversion all energy will be reflected. The longitudinal wave will moreover transform into a transversal (slide tension) wave.

25 The deviation of the angle of incidence to the normal remains limited over a large area with a thicker rock layer. With a thicker rock layer the shock wave can now (for a part) reflect as a traction wave over a larger area
30 and cause spalling. Due to lack of proof it cannot be said for certain whether this is the correct cause.

Besides a large spall area it can be seen that a smaller hole is formed. A hole with a radius of 20 cm in stead of
35 25 cm as in the basic model is probably formed.

Furthermore a statement can be made on the hole which is

- 62 -

formed with a half-infinite rock layer. When it is observed what the failure pattern looks like before and after the shock wave meets the boundary with the gravel the following can be said:

- 5 * With a half-infinite rock layer no spalling will occur.
- * The area with radial cracks only increases from the first 10 cm in the direction of the axis of symmetry.

10 The latter is a result of the geometric reinforcement of the shock wave which was already discussed before.

It can be concluded from above-mentioned findings that with a half-infinite rock layer a hole with the shape of a spherical segment is probably formed. This hole will have
15 a diameter of about 55 cm and a maximal depth in the centre of the hole of about 20-25 cm. It is not inconceivable that moreover a crack goes further into the rock along the axis of symmetry, taking the development of the
20 pressure along this axis into account.

Besides the thickness of the rock layer in reality the composition of the rock layer will be different from place to place. For this reason a simulation was carried out in
25 which the porosity of the rock was taken 10% in stead of 20%. As before it can now be calculated what the material characteristics are going to be. For the strength UCS a doubling was also chosen for, because of which the Mohr-Coulomb criterion and the failure model have been adapted
30 as well. Below all the changes have been summed up:

	basic model	new simulation
n (%)	20	10
K (GPa)	10	16.7
G (GPa)	6	10
ρ (kg/m ³)	2420	2600
UCS	10	20
TS	1	2
y in p=-2 (MPa)	-	0
y in p=-1 (MPa)	0	-
y in p=10 (MPa)	20.45	26
y in p=100 (MPa)	85.2	113
y in p=1000 (MPa)	300	416
failure criterion $\sigma_{i, \max}$ (MPa)	3	6

Table 7: The difference in material characteristics between the basic model and the simulation to determine the influence of the composition of the rock.

With regard to the basic model the load is kept the same. The results of this simulations have been included in figure 28A, B and C. The following can be noted:

- * The crater which occurs as a result of the deformation around the location where the load has been put, is less deep than in the basic model.
- * The course of the pressure in time for the various targets is nearly the same. It can be seen however that the velocity of propagation is higher.
- * The same areas fail, despite a heavier failure

- 64 -

criterion.

- * A clear spall area cannot be found under the crater, possibly because the area has already failed before the traction wave reflects.
- 5 * Because of the higher rigidity of the rock less energy is supplied because of the load: $\pm 20 \text{ kJ}$ instead of $\pm 30 \text{ kJ}$.

10 The influence of the composition of the rock on the breaking behaviour has not become clear with this simulation. Possibly too many parameters at a time have been changed. More examinations are necessary to determine the influence of the composition of rock.

15 From the tests of the basic model it follows that with the annular load a shock wave of about 29 kJ enters the rock layer. This shock wave ensures that spread over a diameter of about 0.5 m , various areas are formed within which the rock fails. Here some pieces may be formed with a maximum
20 size of piece of 10 cm . The rest of the material will be more finely distributed.

It is estimated that about a quarter of the energy released at the explosion of the wire will penetrate the
25 rock layer, so that with this method approximately 120 kJ is necessary, to obtain pieces of maximally 10 cm in a rock layer of 10 cm in thickness. With the crushed volume of 0.02 m^3 the specific energy becomes 6 MJ/m^3 .

30 A shock wave with a low intensity and a long duration of pulse will have rock fail over a larger area than a shock wave with a large amplitude and a short duration of pulse. Here the intensity of the shock wave has to be well above the elastic limit of the material. Knowledge about the
35 height of the elastic limit and the course of the largest main tension as function of the stretch for the one-axis deformation situation around this elastic limit, is impor-

- 65 -

tant for the determination of the most efficient shock wave.

5 An annular exploding wire is an effective way to apply a quantity of energy over a large area in a distributed manner. If it is desired that an area with a radius of 25 cm fails a radius of the load of 20 cm appears to be a good choice.

10 When the rock layer is twice as thick a hole with a radius of 20 cm in stead of 25 cm as in the basic model will probably be formed. When the same load as in the basic model is put on a half-infinite rock layer, a hole with a half-elliptoidic shape will be formed. This hole will have
15 a diameter of about 55 cm and a maximal depth in the centre of the hole of about 20-25 cm.

(16592)

This Sheet Has Been Replaced**Claims**

1. Method for crushing rock, such as for instance concrete, comprising the generation of a shock wave with a preprogrammed form, strength and length of time for crushing rock.
- 5
2. Method according to claim 1, the preprogrammed form, strength and length of time being generated by means of pulsed electric energy.
- 10
3. Method according to claim 1 or 2, in which at least one sparking plug, at least two electrodes between which discharge is generated or a wire conductor is used for generating the shock wave.
- 15
4. Method according to claim 3, in which several sparking plugs are used for generating the shock wave, the sparking plugs being excited in order.
- 20
5. Method for under-water dredging in which the method according to claim 1, 2, 3 or 4 is used.
- 25
6. Method according to any one of the preceding claims, in which the shock wave has such a preprogrammed form, strength and length of time that the crushing of rock produces a desired size of pieces.
- 30
7. Method according to any one of the preceding claims, in which the shock wave has such a preprogrammed form, strength and length of time that the crushing of rock takes place over a desired surface of the rock.
8. Method according to any one of the preceding claims, in



-67-

which the shock wave has such a preprogrammed form, strength and length of time that the crushing of rock takes place up to a desired depth in the rock.

- 5 9. Method for crushing rock, in which a method according to any one of the preceding claims is applied repetitively in different locations placed in or with regard to the rock, in vertical sense and/or in horizontal sense.
- 10 10. Method according to any one of the preceding claims comprising bringing a wire conductor in the proximity of the rock, and having it exploded by means of supplying a pulse-shaped electric energy.
- 15 11. Method according to claim 10, in which the guide is inserted into the rock.
- 20 12. Method according to claim 10 or 11, in which a guide with the shape of a loop or at least almost an annular shape is used as the guide.
- 25 13. Method according to claim 10, 11 or 12, in which during bringing the guide in the proximity of the rock several guide parts are intermittently inserted and each time each guide part is exploded.
- 30 14. Method according to any one of the preceding claims, in which the rock consists of various layers of rock with separation layers in between them, in which the shock wave has such a preprogrammed form, strength and length of time that the crushing of rock is enhanced by reflections of the shock wave from the separation layers.
- 35 15. Device for crushing rock comprising a wire conductor, means for bringing the wire conductor in the proximity of the rock and a device for supplying pulse-shaped electric energy to the wire conductor, with a quantity to have the

This Sheet Has Been Replaced



-68-

wire conductor exploded for generating a shock wave with a preprogrammed form, strength and length of time for crushing rock.

- 5 16. Device according to claim 15, in which the means for bringing the wire conductor in the proximity of the rock are means for inserting the wire conductor into the rock.
- 10 17. Device according to claim 15 or 16, in which the means for bringing the wire conductor in the proximity of the rock comprise means for repetitively bringing new wire conductor in the proximity of the rock.
- 15 18. Device according to claims 15, 16 or 17, in which the means for bringing the wire conductor in the proximity of the rock are means for bringing the wire conductor in the proximity of the rock in the shape of a loop or almost circumferential shape.
- 20 19. Device according to claim 18, in which the diameter of the circumferential shape is approximately 40 cm.
- 25 20. Device according to any one of the claims 15 to 19, in which the wire conductor is placed in a housing.
- 30 21. Device according to any one of the claims 15 to 20, in which the wire conductor has such a shape that the energy released when exploding the wire conductor is aimed at the rock.
- 35 22. Device according to claim 20 or 21 referring to claim 20, in which the housing of the wire conductor has such a shape that the energy released when exploding the wire conductor is aimed at the rock.
23. Manipulator to be used in a device according to claim 17, for repetitively supplying new wire conductor.

This Sheet Has Been Replaced



-69-

24. Device according to any one of the claims 15 to 22, in which the wire conductor is replaced by a means, such as for instance a sparking plug for generating an electrical discharge, which electrical discharge generates the shock wave with a preprogrammed form, strength and length of time for crushing the rock.

25. Assembly of a housing and a wire conductor placed therein, further comprising means for supplying pulsed electric energy to the wire conductor for having the wire conductor exploded and as a result generating a shock wave with a preprogrammed form, strength and length of time, the wire conductor and the housing having such a configuration that the shock wave is aimed.

26. Assembly of a housing and a means placed therein, such as for instance a sparking plug, for generating an electrical discharge, further comprising means for supplying pulsed electric energy to said means for having the media, for instance gasses, surrounding the means exploded by the discharge, and as a result generating a shock wave of a preprogrammed form, strength and length of time, the means and the housing having such a configuration that the shock wave is aimed.

27. Method for crushing rock by means of shock waves, comprising the steps:

- the insertion and/or arranging in the proximity of the rock of at least one electric conductor
- the supplying of a pulse-shaped quantity of electric energy to said conductor and in such a manner, that at least a part of the conductor obtains a pulse-shaped enlargement, through which a shock wave is generated.

28. Method according to claim 27, in which the electric conductor comprises at least two electrodes, such as a sparking plug, which electrodes are at such a distance,

This Sheet Has Been Replaced



* C L M S *

-70-

that in the space between the electrodes an electric arc of electrons can be generated and in such a manner that when supplying the pulse-shaped electric energy the introduction of the electric arc of electrons in said space ensures a pulse-shaped enlargement, by which a shock wave is generated.

29. Method according to claim 27, in which the electric conductor comprises at least one portion of such a cross-section, which is smaller than the remaining portion of the conductor, that when supplying a pulse-shaped electric energy the material changes into the gaseous and/or plasma-shaped phase by a pulse-shaped increase in temperature, resulting in a pulse-shaped increase in volume of the material at the location of said portion and a shock wave is generated.

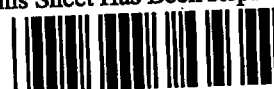
30. Method according to any one of the claims 27 to 29, in which various parts in the conductor have been arranged, which can undergo a pulse-shaped increase in volume and in which the pulse-shaped quantity of electrical energy is supplied to said parts such that they start their pulse-shaped increase in volume in a preprogrammed order.

31. Method according to any one of the claims 27 to 30, in which the pulse-shaped quantity of energy is supplied to the conductor in such a manner, that the generated shock wave has a preprogrammed form, strength and length of time.

32. Method according to any one of the claims 27 to 31, in which a part of the conductor is filamentary.

33. Method according to any one of the preceding claims 27 to 33, in which the form, strength and length of time of the shock wave generated are such that the crushing of the rock results in a desired size of the pieces produced.

This Sheet Has Been Replaced



* C L M S *

-71-

34. Method according to any one of the preceding claims 27 to 33, in which the form, strength and length of time of the shock wave generated are such that the crushing of rock takes place over a desired surface.

5

35. Method according to any one of the preceding claims 27 to 34, in which the form, strength and length of time of the shock wave generated are such that the crushing of the rock takes place up to a desired depth in the rock.

10

36. Method according to any one of the claims 27 to 35, in which shock waves are generated repetitively in the proximity and/or in the rock.

15

37. Method according to any one of the preceding claims 27 to 36, in which repetitively at at least two places in the proximity and/or in the rock shock waves are generated.

20

38. Method according to any one of the preceding claims 27 to 37, in which at at least two places in the proximity and/or in the rock shock waves are generated, such that the start, form, and duration of the shock waves are preprogrammed.

25

39. Method according to any one of the preceding claims 27 to 38, in which at least one part of the conductor, with which the shock wave can be generated, is applied in the shape of a loop or at least almost in an annular shape.

30

40. Method according to any one of the preceding claims 27 to 39, in which the rock consists of several layers of rock with separation layers in between them, that the shock wave generated has such a preprogrammed form, strength and length of time, resulting in increasing the crushing of the rock by reflection waves from the separation layers, which are a result of the shock wave generated.

35

This Sheet Has Been Replaced



* C L M S *

-72-

41. Method according to any one of the preceding claims 27 to 40, in which after treating the soil material of the bed of a water area, the crushed rock material, possibly with other soil material is subsequently removed with the aid of a dredging device.

42. Device for crushing rock by means of shock waves comprising at least one electric conductor, means for bringing the conductor in the proximity and/or in the rock and a device for supplying a pulse-shaped quantity of electric energy to the conductor, which energy is such that at a pulse-shaped increase in volume arises in least one part of the conductor, by which a shock wave is generated.

43. Device according to claim 42, in which the means for arranging the part of the conductor which generates the shock wave in the proximity of and/or in the rock, comprise means, such as a manipulator, to arrange at least said part of the conductor repetitively in the proximity of or in the rock.

44. Method according to claim 42 or 43, in which part of the conductor is filamentary.

45. Device according to claim 42, 43 or 44 in which the means for arranging the part of the conductor which generates the shock wave, in the proximity of and/or in the rock are means for at least arranging said part of the conductor in the shape of a loop or at least in a circumferential shape in the proximity of or in the rock.

46. Device according to claim 45, in which the loop shape or the circumferential shape has a diameter between approximately 0.10 and approximately 2.00 meter.

47. Device according to claim 46, in which the diameter is

This Sheet Has Been Replaced



-73-

between 0.30 and 0.80 meter.

48. Device according to any one of the claims 42 to 47, in which at least the part of the conductor which generates the shock wave is placed in a housing.

49. Device according to any one of the claims 42 to 48, in which at least the part of the conductor which generates the shock wave has such a shape, that the shock wave generated is directed at the rock in concentrated form.

50. Device according to claim 48, in which the housing has such a shape, that the shock wave generated is directed at the rock in concentrated form.

51. Manipulator to be used in a device according to claim 43, for repetitively supplying a part of the conductor which generates a shock wave.

52. Device according to any one of the claims 42 to 50, in which the pulse-shaped quantity of electric energy is supplied to the conductor in such a manner, that the shock wave generated has a preprogrammed form, strength and length of time.

53. Assembly of a housing with a filamentary electric conductor placed therein, means for supplying a pulse-shaped quantity of electric energy to the conductor and having a shock wave generated through that with a preprogrammed form, strength and length of time, in which the part of the conductor which generates the shock wave and the housing have such a configuration that the shock wave generated is directed at the rock to be crushed in concentrated form.

(NG 2075)

This Sheet Has Been Replaced

